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Nanoscale Structured Illumination Microscopy with Extreme-Ultraviolet Ultrafast Transient Gratings

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Visualizing nanostructures within macroscopic materials is fundamental to understanding their physical and chemical properties. Over the past decades, super-resolution techniques have revolutionized visible-light microscopy [1-3]. Among these, structured illumination microscopy (SIM) [4-6] provides a straightforward implementation to access a full range of spatial information limited by the Abbe limit.
Achieving nanometer-scale spatial resolution together with high temporal resolution extends the investigation to ultrafast material dynamics. Free-electron laser (FEL) sources are well-suited for this purpose, delivering fully coherent, ultrashort pulses at nanometer wavelengths.
To implement SIM with FEL pulses [7], we employed the extreme-ultraviolet (EUV) transient grating (TG) technique, which generates a sinusoidal intensity modulation by crossing two ultrafast and fully coherent FEL beams [7,8].
This structured illumination setup, combined with a fluorescent system, allows us to reconstruct sample details beyond the diffraction limit by exploiting Moiré fringes created by the interference between the sample's spatial frequencies and the structured beam. The modulation periodicity can be tuned down to a few nanometers [9] by adjusting the FEL wavelength or crossing angle.
Using this approach, we have improved the performance of previous studies, achieving nanometer-scale spatial resolution by exploiting the tunability of FERMI FEL. Since this method employs ultrafast pulses, it enables time-resolved studies, allowing not only the visualization of nanometric details but also the potential investigation of their dynamics.
The system's ability to detect fluorescence across a broad spectral range makes it applicable to nanostructures, disordered molecular systems, and phase transitions in mesoscopic materials. It could also be used for imaging biological specimens, quantum materials, and nanoscale defects in optoelectronic devices, providing a powerful tool for high-resolution imaging in different research areas.
Future developments include adapting the setup for the hard X-ray regime by replacing the visible objective with an X-ray zone plate for X-ray fluorescence detection. The X-ray optics are being fabricated.
Performing SIM using pulsed X-ray sources will open new opportunities for studying dynamic processes, such as phase transitions and catalytic reactions. The next step involves implementing X-ray structured beams with sub-10 nm periodicity, combined with X-ray fluorescence imaging. This would remove the need for optically fluorescent samples while enabling high-resolution elemental and chemical mapping. Additionally, the short lifetime of X-ray fluorescence eliminates the need for optical up/down-conversion techniques to achieve ultrafast temporal resolution.

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Workshop topics

Applications

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